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FORCE CANCELLATION MOTOR

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Abstract

This paper presents the Force Cancellation Motor (FCM), a microspeaker concept designed to reduce vibrations in ultra-thin mobile devices without increasing module height. FCM integrates a compact actuator into the speaker's center magnet, enabling active vibration suppression based on the known excitation signal while remaining independent of acoustic output. Prototype measurements show strong vibration reduction in perceptually relevant low-frequency ranges and a 71% power-efficiency improvement over a height-optimized dual-woofer reference. Additional benefits include optional activation of the compensation feature and the actuator's use as a haptic driver, making FCM a promising solution for space-constrained audio systems.

Keywords: *Microspeaker, force cancellation, active vibration reduction*

1. Introduction

One of the major challenges faced by audio engineers is achieving high-performance sound, particularly in the low-frequency range, while avoiding unwanted mechanical vibrations. Traditional methods of dealing with these vibrations often present significant compromises, especially in thin, modern laptops. However, this innovation - a micro speaker woofer with an integrated actuator - offers a revolutionary approach by providing superior acoustic performance without increasing the footprint or sacrificing design flexibility. This paper explores the limitations of conventional solutions and explains the technical advantages of this force cancellation technology.

2. The Problem

When a woofer works at low frequencies, it produces significant mass movement, which is transmitted to the device via the law of conservation of momentum.

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These vibrations are problematic for the following reasons:

- **Acoustic Distortion**:The vibrating surface of a mobile device acts as DML (Distributed Mode Loudspeaker) and creates unwanted soundwaves which sum up with the speakers output leading to bass modulated artefacts. What's more these vibrations can stimulate rattling of the keyboard.
- **User Experience**: The vibrations are transmitted to the user, which can be distracting, whether you're typing on the keyboard or just holding the mobile device.
- **Device Integrity** Uncontrolled vibrations can cause wear and tear on internal components, leading to potential hardware issues.

3. State-of-the-art solutions

3.1. Passive Damping Solutions

The industry has explored various methods to counteract these vibrations. While traditional damping solutions, such as the use of isolation materials, provide some relief, they come with significant drawbacks in terms of space and efficiency.
Beyond mechanical damping, dual-woofer systems are among the most widely used approaches for vibration control. However, these solutions also have inherent limitations, particularly in thin laptop designs.

3.2. Double Woofer Systems (Stacked Configuration)

- **Mechanism and advantage**: In this configuration, two woofers are stacked on top of each other and are wired to move in opposite directions, adding their acoustical output while canceling out their respective forces. In other words this configuration solves the vibration topic sufficiently.
- **Disadvantage**: Although this approach is optimal by means in suppressing forces efficiently, it doubles the z-height of the audio system. Beside that sound quality and force cancellation both depend on synchronous movements of both

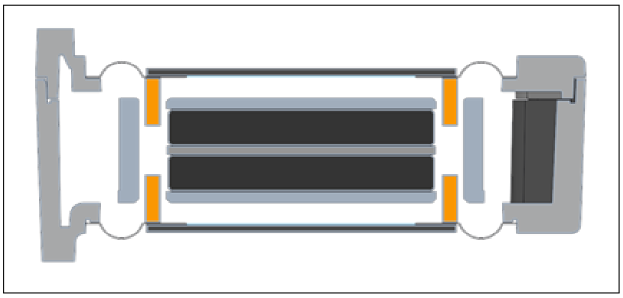

Figure 1: Cross-section of a stacked double woofer concept

woofers which requires additional space to combine the front and rear sound ports symmetrically.

3.3. Side-by-Side Woofers (Horizontal Configuration)

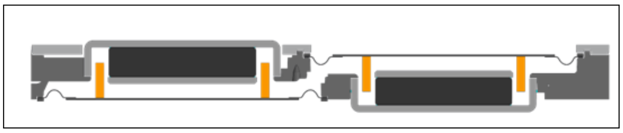

Figure 2: Final speaker module showing the dimensions

- **Mechanism and advantage**: Two woofers are placed side-by-side in the x and y directions, again running in opposing phases to counteract vibrational forces.
- **Disadvantage**: While this configuration avoids the z-height issue, it doubles the footprint in the x or y direction. The space and especially the symmetry requirements mentioned above is even more critical for this side-by-side configuration as the rear ports connected to the back-volume needs to be symmetrical in x and y dimensions. Additionally, off-axis cancellation is less effective because the two opposing forces must be balanced by an external mechanical structure.

4. FCM Technology

4.1. Background

The principle mentioned above - placing two identical speakers piggyback - is well known and proves to be very effective and energy-efficient if the symmetry requirements for front and back porting are met. More complex speaker arrangements based on that principle can be found in the literature[1]. A completely different approach needs to be used if the source of vibration is unknown and needs to be controlled in real-time. Using a loudspeaker-based inertial actuator this can reduce vibration significantly but also faces limitations due to the complexity[2]. The Force Cancellation Motor Technology can be understood somewhere in between. On the one hand, we know the signal that causes the vibrations, but we want to dampen these vibrations using a completely different dynamic system. The innovative solution discussed in this paper overcomes the shortcomings of traditional methods by integrating an actuator into the center magnet of a single woofer.

4.2. How it works

The initial height requirement for this speaker system, including headroom for tolerances reads 4 mm. The basic idea is to integrate the actuator into the speaker's central magnet, taking into account the entire range of motion as well as the necessary tolerances. The height of the center magnet must be at least equal to the peak-to-peak excursion of the speaker, making it impossible to position the actuator such that it has the same excursion. To solve this problem we look at Newton's Second Law:

$$F_{spk} = m_{spk}\, a_{spk} \tag{1}$$

Assuming harmonic steady-state motion and linear system behavior, the equation can be reformulated for the speakers' force:

$$F_{spk} = r\, m_{act}\, \frac{a_{act}}{r} \tag{2}$$

The ratio of actuator mass and speaker mass results in the excursion reduction factor r

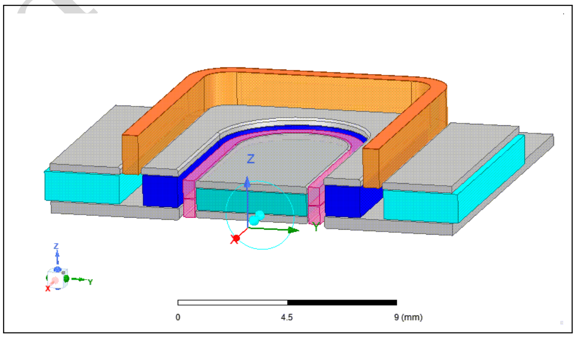

Figure 3: Principle of Force cancellation Motor

With the help of this concept, the space requirement of the counterforce-generating part can be reduced to zero.

4.3. Dependencies

Although vibration suppression no longer depends on the symmetry of two acoustic systems, there are still some factors in the FCM design that must be taken into account:

- **Area within the speaker coil**: This area must be large enough to accommodate the actuator and a ring-shaped magnet.
- **Reduction factor**: The available space for the actuator, including its excursion, determines the permissible moving mass of the loudspeaker as well as the possible excursion, which in turn affects the actuator's installation space.

- **Effective area of speaker**: The dependencies mentioned above can be easily achieved by using the largest possible voice coil and diaphragm area. Unfortunately, there is also a limitation here that affects acoustic efficiency at low frequencies: The larger the diaphragm area, the stiffer the air spring against which the diaphragm must work.

5. First steps

5.1. Compensation approaches

Ultimately, vibration compensation requires two opposing forces. In the traditional approach using two identical speakers, this is achieved through the symmetry of the components. In the FCM concept, however, we deliberately separate the acoustic response from the force compensation, which means that we must know the force imparted by the speaker and instantaneously drive the actuator with a correspondingly filtered signal.

5.2. Linear and non-linear modeling

Figure 4 shows the simulated time signal for the speaker and actuator based on non-linear modeling and optimized to match each other.

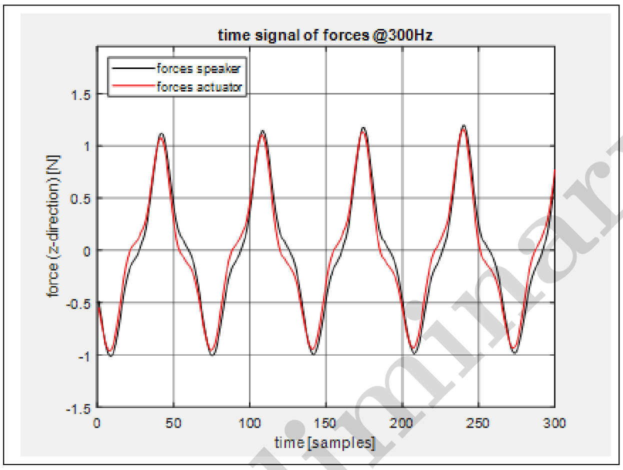

Figure 4: Time signal of forces for modeled speaker and actuator

5.3. First mockup samples

A first approach to prove the simulated concept on a real-world sample is shown on a mockup sample in figure 5, where an actuator is glued piggyback on a microspeaker. This setup is mounted in a grey housing where an acceleration sensor is attached to the surface. Using a real-time simulation and testing environment (Simulink Real-Time™ and Speedgoat system) we are able to demonstrate the principal mechanism to work for linear modeling as well as for non-linear modeling. Although the modeled forces show good agreement at both the speaker and the actuator, the vibration damping—at approximately 3 dB—is insufficient.

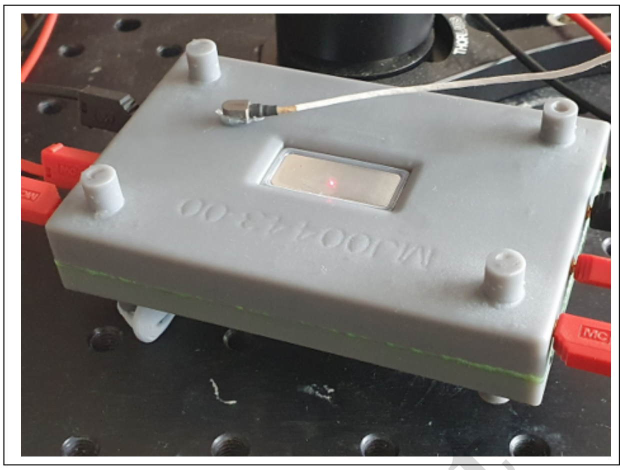

Figure 5: First mockup sample with acceleration sensor glued close to the speaker

5.4. Vibration perception thresholds

The requirements for vibration suppression in this field of application are well studied in [3]. Figure 6 shows the critical frequency range as well as the vibration sensitivity over frequency together with the measured values of the final showcase demonstrator. This limited frequency range of finger sensitivity supports our approach of separating acoustic and vibration suppression. In contrast, a traditional two-speaker solution needs to match the acoustic behavior across the entire frequency range, even though, for example, vibration is hardly perceived @ 1.5 kHz.

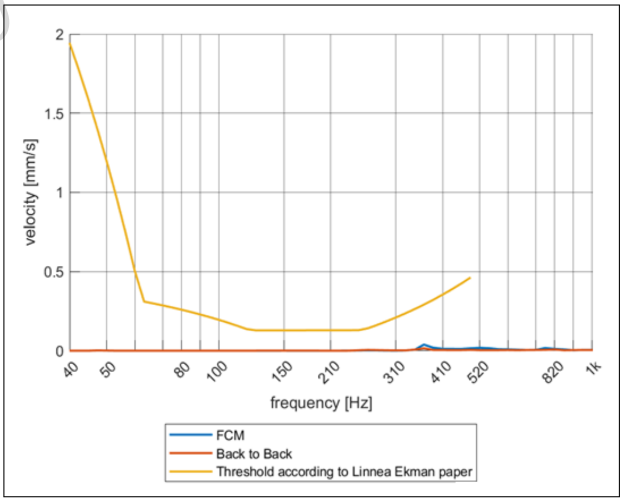

Figure 6: Vibration sensitivity threshold over frequency

5.5. Compensation strategy

The preceding paragraphs show that applying a modeled signal manipulation (both linear and nonlinear) to the actuator can be used to balance the resulting forces of the two different components. At the same time, however, it has also become clear that the connection to the housing must be taken into account in order to ultimately minimize vibration there. Applying linear system theory, one determines the transfer functions of the two systems and uses them to generate the correction filter for the actuator. Since we are dealing here with a mixture of linear and nonlinear systems, we choose the following approach: For each applied frequency in the steady-state condition, we seek the optimal gain-phase relationship between the speaker and actuator signal that minimizes vibration at a specific point on the housing. Figure 7 shows the empirical frequency response of the final showcase demonstrator.

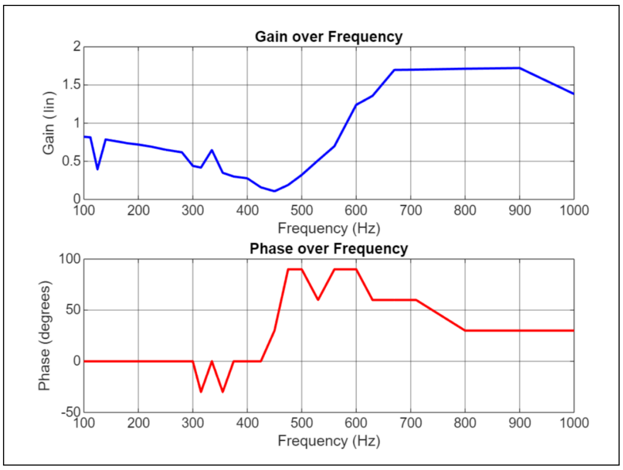

Figure 7: Frequency dependent gain and phase settings for actuator referenced to speaker

5.6. Component

As discussed in chapter 4.2 the actuator is placed within the center magnet of the speaker and underlies height restrictions. Furthermore, due to the symmetry of the component, the centers of gravity of the actuator magnet assembly on one side and the diaphragm-coil assembly on the other coincide with respect to the x and y components, which corresponds to the configuration of a conventional two-speaker system. The final

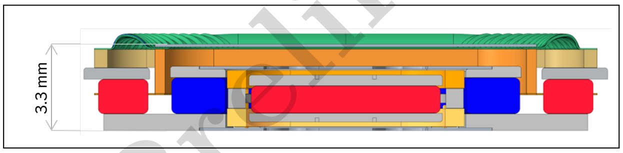

Figure 8: Cross-section of a side-by-side double woofer concept

design can be seen as a crosscut in figure 8. Note that the magnet colors in red and blue denote the magnetization direction. This refers to another dependency beside mechanics and acoustics: the interaction between two magnet circuitries. Due to this ring shaped blue magnet a good magnetic isolation between the speaker and the actuator can be achieved which eases the tuning of the final module.

Figure 9 shows the backside of the FCM component revealing the S-shaped actuator spring on top. The gap between this spring and the moving magnet reads 125 µm nominal.

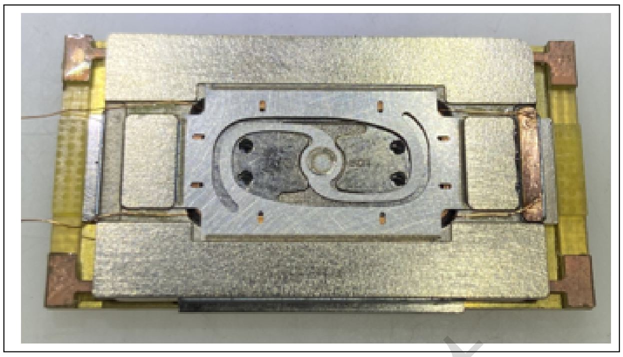

Figure 9: Backside view of the FCM component

6. Results

6.1. Reference design

All of our subsequent descriptions and considerations refer to a reference design[1] based on a traditional two-way speaker configuration. In order to reduce the height of the piggyback speaker assembly, a recently filed and published speaker configuration is used[4]. The final module designs of FCM (top) and reference design (bottom) can be seen in figure 10. Both share the same module dimensions, the same rear volume, and can displace the same amount of air.

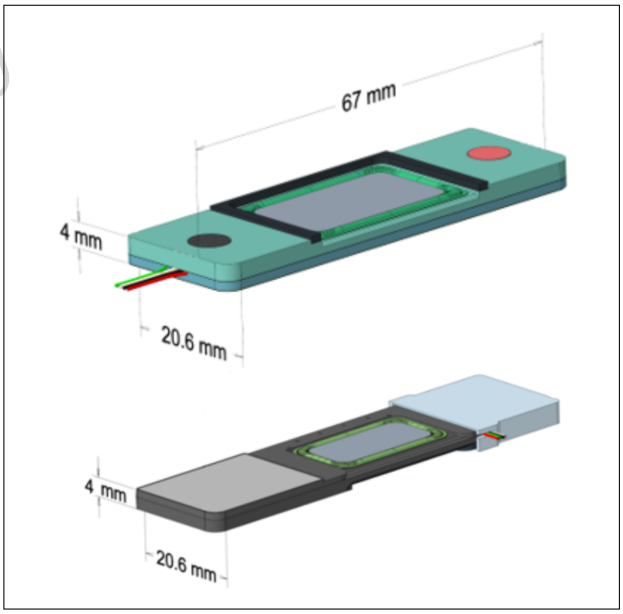

Figure 10: Reference design placed in module

Note the surface area (SD) of the reference design-speaker, which doubles when combined with the symmetrical speaker on the bottom of the module. Thus, the total surface area is larger than in the FCM design under consideration. To achieve comparable sound

[1]Referred to as back to back as well

pressure, the FCM's diaphragm must therefore move further to displace the same volume of air. To ensure a fair comparison, we need to set both systems to the same sound pressure level and then compare their power consumption and other parameters.

6.2. Impedance

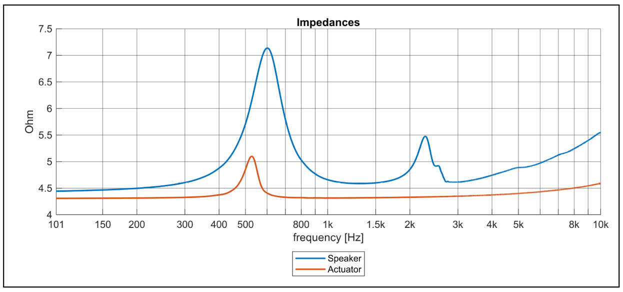

Figure 11: Impedance of speaker and actuator

An important characteristic of loudspeakers and actuators is their impedance response shown in figure 11, which reveals their main resonance, damping as well as other artifacts. The blue curve denotes the speakers' impedance measured in the module characterized by the main resonance @ 600 Hz and a second resonance peak corresponding to the break-up mode. The red impedance curve of the actuator shows a slightly lower resonance frequency for the actuator. Figure 12 shows the impedance of the reference design.

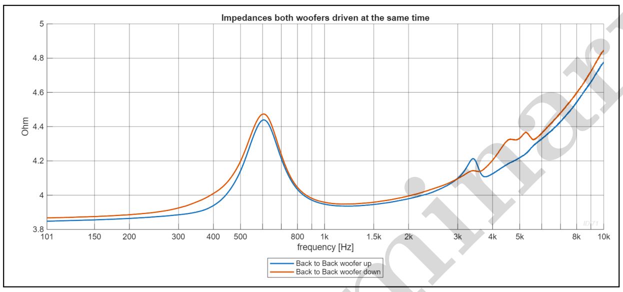

Figure 12: Impedance of reference design

6.3. Large Signal Frequency response

All electroacoustic measurements are based on a standardized setup. For this purpose, the module (FCM or reference design) is mounted on a rigid plastic plate (200 x 300 x 5mm) which is suspended on rubber bands approximately 1 cm above a 60 × 60 cm Thorlabs plate. The microphone is mounted 5 cm in front of the side-port, parallel to the Thorlabs plate. The vibration is monitored by a laser vibrometer targeting one point on the surface of the module under test. Figure 13 shows both frequency responses and the frequency range of interest in green. The reference design is driven with a logarithmic sweep @5 V_{RMS} whereas the FCM module is tuned to reach the same SPL-levels up to 1.5 kHz (green area) as we focus our conclusions on woofer performance.

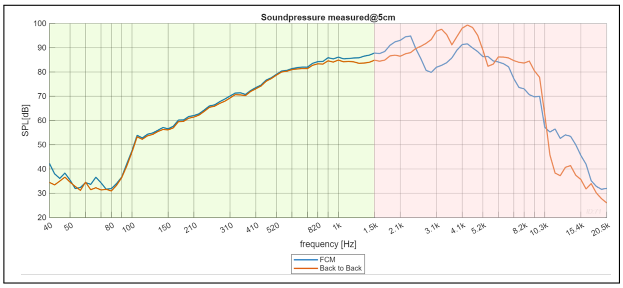

Figure 13: Frequency response of FCM and the reference design

6.4. Force cancellation

As mentioned in Section5.5, the vibration is measured at a single point to determine the optimal values for the filter coefficients. Figure 14 now shows the resulting vibration damping on a logarithmic scale compared to the actuator turned off.

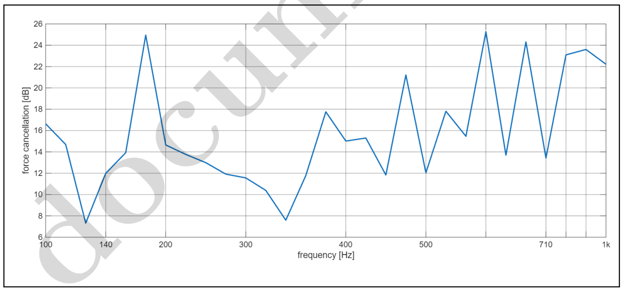

Figure 14: Force cancellation performance ON vs. OFF

6.5. Power efficiency

Figure 15 shows the power consumption of the reference design with the curves for the individual drivers being nearly identical.

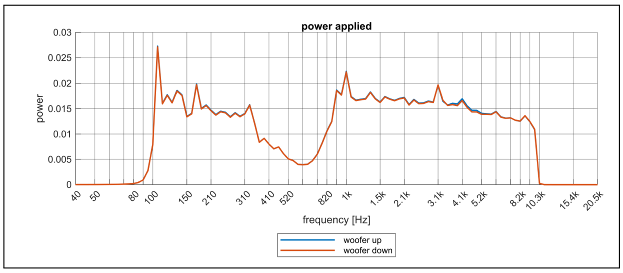

Figure 15: Ref. Design: each driver (red, blue)

The power consumption of the FCM is entirely different: the actuator is active only up to 1 kHz resulting in a much lower averaged power consumption.

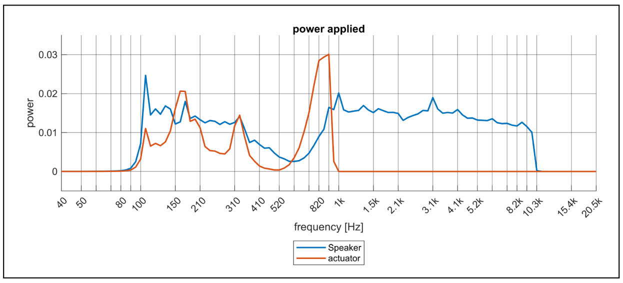

Figure 16: FCM:speaker (blue) and actuator (red)

The final energy efficiency is determined using the following equation: First, we calculate the ratio of the sound power output to the electrical power input for both designs.

$$\text{ratio}_{\text{FCM}} = \frac{\text{RMS}_{\text{mic}}^2}{P_{\text{speaker}} + P_{\text{actuator}}} \tag{3}$$

and for the reference design:

$$\text{ratio}_{\text{back2back}} = \frac{\text{RMS}_{\text{mic}}^2}{P_{\text{woofer,up}} + P_{\text{woofer,down}}} \tag{4}$$

In a second step we calculate the performance gain by applying following formula:

$$\text{Powerefficiencygain} = 100\,(\frac{\text{ratio}_{\text{FCM}}}{\text{ratio}_{\text{back2back}}} - 1) \tag{5}$$

which can be seen from figure 17 resulting in an averaged efficiency gain (100 Hz - 1.5 kHz) of **71%** for FCM.

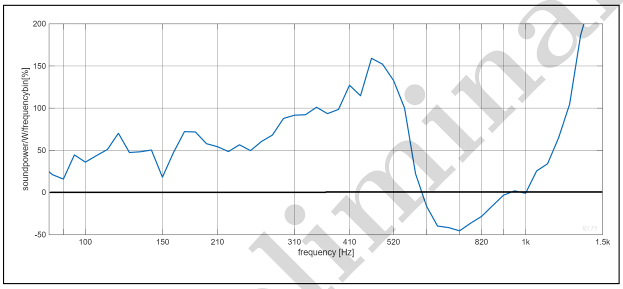

Figure 17: Powerefficiency gain of FCM compared to the reference design [%]

7. Further benefits

In addition to the power efficiency advantage mentioned above, there are other benefits compared to the reference design:

- This system comparison focused on a low-frequency application in which the break-up mode of the speaker found @ 2.5 kHz is not an issue. However, the FCM concept presented here is also fundamentally suitable for driving a full-range loudspeaker, provided that the break-up mode frequency is shifted up accordingly. For the reference design, however, the symmetry condition for the connection to the rear and front enclosures must also be met for this extended frequency range.
- The actuator can be used standalone as haptics engine.
- The force compensation feature can be easily turned on and off (energy-saving mode).

8. Conclusion

This paper demonstrates not only how a novel acoustic component can be developed but furthermore the efforts needed to rate and show the benefit. The results demonstrate that a design combining a diaphragm with an additional actuator can outperform conventional solutions that inherently provide vibration suppression. The results indicate that even though it is possible to simply scale down well-known, well-functioning structures, in such a complex system the rules of the game change, and other solutions - which, as shown here, initially seem hopeless - turn out to be the better choice. The 71% improvement in efficiency is not so much due to the FCM's speaker performing significantly better. Rather, the reason lies in the relative deterioration of the reference design caused by the height limitations of the module. The space required for the necessary tolerances in the mirrored diaphragm systems of the reference design significantly reduced the size and thus the power of the magnetic circuit.

9. Acknowledgments

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